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The impact of a wind variable generation on the hydro generation water shadow price

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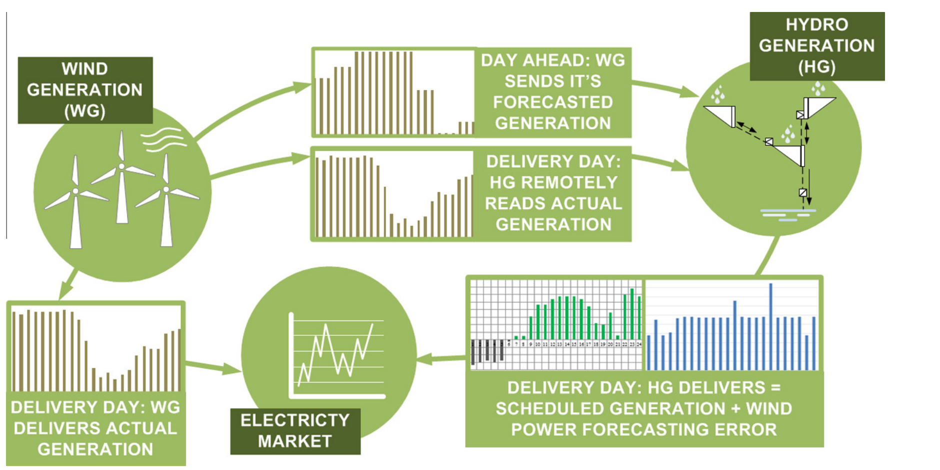
HIGHLIGHTS

- The papers addresses a coordinated hydro and wind generation.
- A model for obtaining the water shadow price is presented.
- The effects of wind forecasting errors on water shadow prices are examined.

GRAPHICAL ABSTRACT



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ABSTRACT

The volatility and complex forecasting methods of fluctuating wind generation is a growing issue. From a system perspective, this introduces additional issues regarding demand and supply balancing and also creates the need for more balancing capacity. One of the best supplements to volatile wind nature is certainly hydro generation, especially in complement with pumped storage technology. Water can provide large backup capacity and flexibility to balance wind deviations. In this research short-run hydro–wind coordination is addressed and an approach based on the duality method of a convex programming is proposed, for valuing the impact of variable wind generation on the water shadow price of hydro generation. In such hydro–wind coordination, hydro generation is committed for the differences between the actual and forecasted wind generation. Obtaining water shadow prices is important for determining short-run marginal cost and economic feasibility assessment of this coordination. The proposed method solves short-run profit maximization, as its primal problem, and determines the values of limited hydro and wind resources, as its dual problem, using a linear programming approach. The coordination between the Vinodol hydropower plant and the Vrataruša wind farm in Croatia is presented as a case study.

1. Introduction

Electricity systems have transformed significantly during the last decade – from deregulation to increased amounts of renewable

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Nomenclature

Parameters

k_{St}	maximal capacity of reservoir, $k_{St} \in \mathbb{R}^+$ (MW h)
n_{St}	minimal capacity of reservoir, $n_{St} \in \mathbb{R}^+$ (MW h)
k_{Tu}	hydro turbine maximal capacity, $k_{Tu} \in \mathbb{R}^+$ (MW)
n_{Tu}	hydro turbine minimal capacity, $n_{Tu} \in \mathbb{R}$ (MW)
k^w_{Tu}	wind turbine maximal capacity, $k^w_{Tu} \in \mathbb{R}^+$ (MW)
n^w_{Tu}	wind turbine minimal capacity, $n^w_{Tu} \in \mathbb{R}^+$ (MW)
e	natural water inflow, $e \in L^\infty_+[0,T]$ (MW)
d	difference between actual generation y_w and forecasted wind generation Y i.e. the wind power forecasting error $d \in L^\infty[0,T]$ (MW) (Fig. A1)
d^+	surplus of wind generation (positive part of wind power forecasting error, d), $d^+ \in L^\infty_+[0,T]$ (MW) (Fig. A1)
d^-	shortage of wind generation (negative part of wind power forecasting error, d), $d^- \in L^\infty_-[0,T]$ (MW) (Fig. A1)
π	price of electricity, $\pi \in L^1[0,T]$ (MW)
y_w	actual wind generation, $y_w \in L^\infty_+[0,T]$ (MW)
Y	contracted wind generation $Y \in L^\infty_+[0,T]$ (MW)
s_0	energy stock at the beginning of planning interval, $s(0) \in \mathbb{R}^+$ (MW h)
s_T	energy stock surplus or deficit at the end of planning interval, $s(T) \in \mathbb{R}$ (MW h)
ρ	slope of the performance curve (MWs/m^3).

Functions

y	hydro generation $y \in L^\infty[0,T]$ (MW).
φ	spillage, $\varphi \in L^\infty_+[0,T]$ (MW)
g	net outflow of hydro generation, $g \in L^\infty_+[0,T]$ (MW)
s	energy stock, amount of water in reservoir in $t, s \in \mathrm{Lip}^c[0,T]$ (MW h)
κ^{Tu}	shadow price of hydro generation maximum capacity, $\kappa^{Tu} \in L^1_+$ (€/MW)
ν^{Tu}	shadow price of hydro generation minimum capacity, $\nu^{\mathrm{Tu}} \in L^1_+$ (€/MW)
κ^{St}	shadow price of reservoir's maximum capacity, $\kappa^{St} \in L^1_+$ (€/MW h)
ν^{St}	shadow price of reservoir's minimum capacity, $\nu^{St} \in L^1_+$ (€/MW h)
λ	shadow price of energy stock surplus or deficit at the end of planning interval, $\lambda^{St} \in L^1_+$ (€/MW)
ψ	shadow price of water, $\psi \in L^1_+$ (€/MW h)

Spaces

$[0,T]$	planning interval, subspace of the real line $t \in [0,T] \subset \mathbb{R}$
$L^p([0,T])$	the space of equivalence classes w.r.t. μ (Lebesgue measure) of measurable functions $f : [0,T] \to \mathbb{R}$
$L^\infty([0,T])$	the space of equivalence classes w.r.t. μ (Lebesgue measure) of essentially bounded measurable functions

energy. Specific features of renewable energy sources require appropriate organization of both power system and market integration. Presently in some countries (Germany, Spain, UK and others) [1] renewable energy sources are exposed to balancing risk i.e. the risk of financial penalization of production plan (forecasted generation) deviations. In such conditions, wind farm owners are seeking out risk mitigation mechanisms.

Generally, hydro generation produces electricity from storable water, while wind generation produces electricity from the non-storable input of wind energy. Having in mind the high flexibility and the favorable maximum sustain ramp rate (MW/min) of hydro generation, there is a good reason for committing hydro generation for firming wind generation i.e. in order to balance the differences between actual and forecasted wind generation, from now on referred to as wind power forecasting error. In this coordinated operation, the wind power forecasting error induced by intrinsic wind volatility surely impacts the optimal hydro generation schedule and therefore the water shadow price.

Generally, the shadow price of a constraint is the instantaneous change of the objective value of the optimal solution, per unit of the right hand side (r.h.s.) of a constraint in concern in the optimization problem i.e., it is the marginal utility of relaxing the constraint, or, equivalently, the marginal cost of strengthening the constraint. In this paper, water shadow price in a particular hour (t) is the instantaneous change in the profit maximization objective function when using one cubic meter of water in the hour (t) and withdrawal of one cubic meter of water from other hours $[0,T] \setminus \{t\}$. This withdrawal from other hours results in an opportunity cost, and since the withdrawal actually strengthens constrains in other hours $[0,T] \setminus \{t\}$, the opportunity cost is actually and by definition the marginal cost of water usage. Thus for the particular hour, the water opportunity cost, the water marginal cost and the water shadow price are synonymous. Further on in this paper the expression "water shadow price" is used.

Defining the water shadow price as the marginal cost is important since the direct cost of hydro generation is virtually zero compared to fossil fuel generation, where short-run marginal cost curve is obtained by the first derivative of the short-run total cost function. If this standard approach is used, the marginal cost curve of hydro generation would be zero, which would misrepresent the actual costs [2]. These costs are the opportunity costs of water usage and result from the fact that water is a limited resource in the short-run and can only be used or stored in order to increase profit. This is not the case with fossil fuels, where fuel is considered to be always available in the short-run.

The motivation for this research lies in the following issues: (a) the lack of historical data on wind speed in Croatia results in a yearly average day-ahead wind power forecasting error (mean absolute percentage error) of 11.1%; (b) it is expected that the installed capacity of wind power in Croatia will increase from 350 MW to 1200 MW by 2020 [3]; (c) the need for a systematic approach to evaluating the influence of wind generation on hydro generation which provides frequency regulation (in Croatia, frequency regulation is entirely provided by hydro generation); (d) the need for mitigation of the balancing risk for wind farm owners. Presently in Croatia wind generation is not exposed to balancing risk, since all generation mismatches due to forecasting errors are paid by the end-users. This, however, is expected to change [3], especially after the adoption of the new Guidelines issued by the European Commission which recommend more market-oriented wind generation [4].

This paper is based on innovative research [5–7] that systematically address the problem of short-run profit maximization of hydro and pumped storage units using continuous functions. Another early research on hydro-thermal dispatch cost minimization is [8], which does not ensure unique shadow prices pointed out in [9]. All these articles are based on the ideas of conjugate duality and optimization [10]. In the last decade hydro–wind